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AFRL-SR-AR-TR-04-

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1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE	3. REPORT TYPE AND DATES COVERED 05 Jan 2004 - 04 Jul 2004 FINAL	
4. TITLE AND SUBTITLE (STTR Phase 1) Photonic Crystal Chip-Scale Optical Networks			5. FUNDING NUMBERS 65502F STTR/TX	
6. AUTHOR(S) Dr Dobson				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) SILICON OPTICS INC 11781 LINE PEAK PKWY S200 DRAPER UT 84020-6883			8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NE 4015 WILSON BLVD SUITE 713 ARLINGTON VA 22203			10. SPONSORING/MONITORING AGENCY REPORT NUMBER FA9550-04-C-0023	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A: Unlimited			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) We have invented a new approach to minimize losses in PC components through the use of vertical mode matching within the slab and lower index pillars, such that out of plane scattering is virtually eliminated. We are also investigating methods to incorporate this technique into SQL-based systems. Ultimately (Phase 11), the types of PC components we plan to build are based upon the ability of PC structures to modify of the photonic density of states. The target devices are thermo-optic tunable wavelength filters, add/drop multiplexers, and nonlinear optical switches and wavelength converters, although other forms of active control (such as carrier-effect modulation) and nonlinear optical operations can be considered.				
<div style="text-align: center;">BEST AVAILABLE COPY</div> <div style="text-align: right; font-size: 2em; font-weight: bold;">20041110 016</div>				
14. SUBJECT TERMS			15. NUMBER OF PAGES	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT Unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified	20. LIMITATION OF ABSTRACT UL	

Silicon Optics/University of Utah STTR: Photonic Crystal Chip-Scale Optical Networks

Final Status Report (1/5/04-8/13/04)

Overview and Objectives

The objective of our program was to develop a hybrid approach to enable localized placement of photonic crystal (PC) slab devices for chip-scale optical networks consisting of a multitude of WDM channels. The purpose of the hybrid approach is to utilize more traditional low to medium index contrast integrated optics for signal routing, impedance matched with photonic crystal components for signal manipulation. We have invented a new approach to minimize losses in PC components through the use of vertical mode matching within the slab and lower index pillars, such that out of plane scattering is virtually eliminated. We are also investigating methods to incorporate this technique into SOI-based systems.

Ultimately (Phase II), the types of PC components we plan to build are based upon the ability of PC structures to modify of the photonic density of states. The target devices are thermo-optic tunable wavelength filters, add/drop multiplexers, and nonlinear optical switches and wavelength converters, although other forms of active control (such as carrier-effect modulation) and nonlinear optical operations can be considered. By properly engineering the density of states for transport across multiple, coupled PC defects, these devices can operate at high speeds with low power. For example, due to the tight confinement of light in a PC defect (resulting in volume $\sim \lambda^3$), the thermo-optic effect can be used to great advantage as switching time is determined by thermal conduction across an extremely small volume, and the enhanced density of states means that only a small thermo-optic increase in refractive index is needed for switching. These PC devices will be interconnected using standard, lower-loss channel waveguides to minimize overall system loss.

The following section describe our recent progress in the areas of reducing out of plane scattering losses and initial designs and simulations of slow-light Mach-Zehnder interferometers.

Reduction of out of plane scattering losses by the use of vertical mode-matching

In standard PC slabs, the out-of-plane loss depends strongly on the vertical index contrast of the slab [bogaerts02], reaching its minimum values for both very low index contrast and high index contrast, where in the latter case loss-less Bloch modes are excited. Even in the Bloch mode case, loss-less propagation only occurs for an infinitely-extended, perfectly-periodic structure; therefore, even simple structures such as defects can introduce out-of-plane scattering. An additional problem that arises in heterostructure slabs is the depth and quality of etched air holes, where the loss is minimized for an etch depth greater than the vertical mode profile width, but the quality of deep etching (in terms of maintaining a constant hole diameter) is limited by an aspect ratio of roughly 10:1 [krauss03].

The generic geometry of our method is shown in two-dimensional cross-section in Figure 1. For a membrane PC, $n_{1a}=n_{1c}=n_{2a}=n_{2b}=n_{2c}=1$, whereas for a standard heterostructure slab PC, $1 < n_{1a}=n_{1c} < n_{1b}$, and $n_{2a}=n_{2b}=n_{2c}=1$; in both cases, there is no mechanism for vertical confinement within the holes. In order to introduce vertical confinement within the holes, we must have the condition $n_{2a}, n_{2c} < n_{2b}$. Ideally, the refractive indices are such that the vertical mode profile in the holes

matches that of the slab as determined by a mode overlap integral. In many cases, this integral can equal 1, indicating exact vertical mode matching.

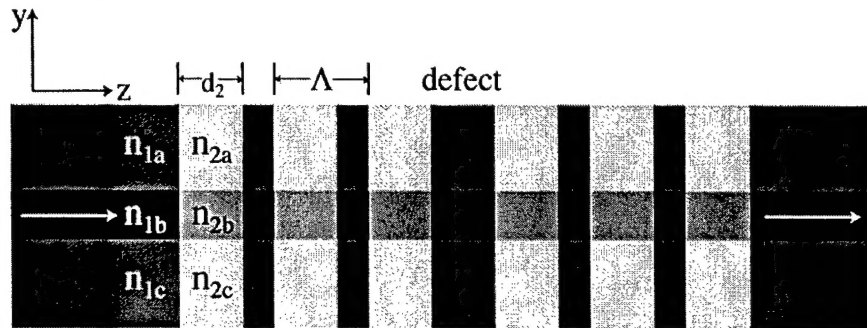
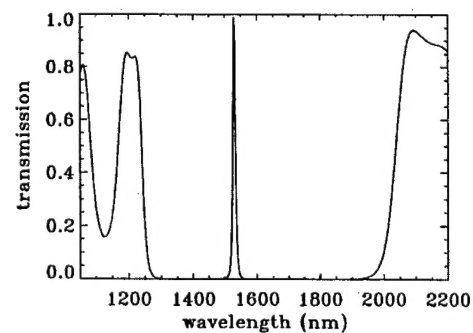
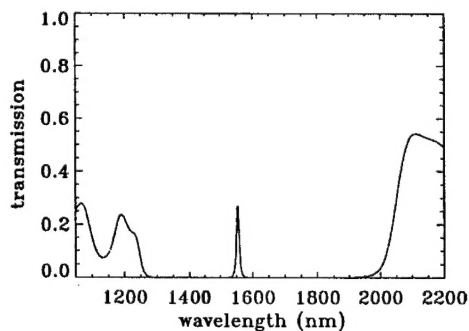
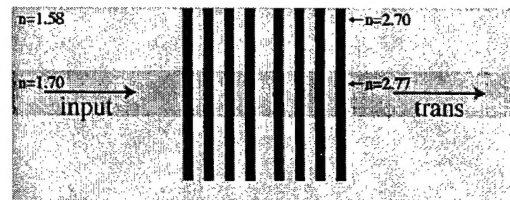
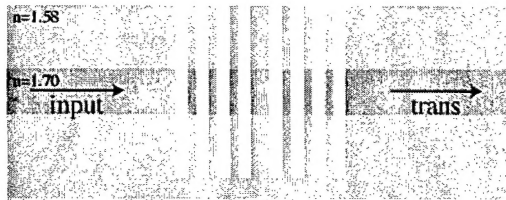


Figure 1. Cross-section illustration of photonic crystal slab structure that promotes vertical mode matching within the slab and hole.

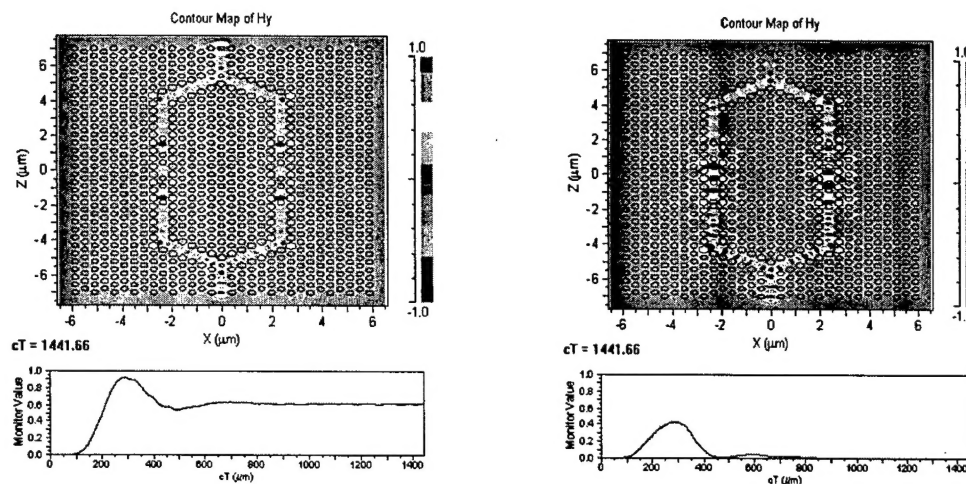
We have performed extensive FDTD modeling studies of this structure and its comparison with air-hole PC slabs [blair04]. One example is shown in the following figures, where the structure with vertical mode matching (right) results in nearly 100% transmission of a photonic crystal defect resonance while the air hole structure (left) has reduced transmission of 28%. As the quality factor of the defect cavity increases, the loss of the air hole structure increases but the structure with vertical mode matching maintains nearly 100% transmission. When the same refractive indices are used in a 2-D triangular lattice, the structure with vertical mode matching has nearly the same bandgap width as the air hole structure for TM modes. This bandwidth is sufficient to cover the S-, C-, and L-, telecom bands.



Slow-light Mach-Zehnder interferometer

We have also been working on the design and simulation of a slow-light Mach-Zehnder interferometer [soljacic02] for use as a thermo-optic switching device to be demonstrated in Phase II. The following figures show FDTD simulation results of the "on" and "off" states of the device, where the "off" state is produced by a small refractive index change (about 1%) of a defect array. Further optimizations will reduce the required change to below 0.1%. We have

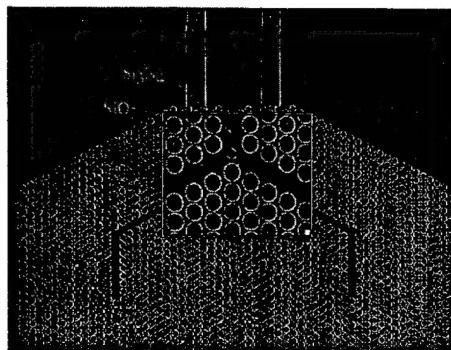
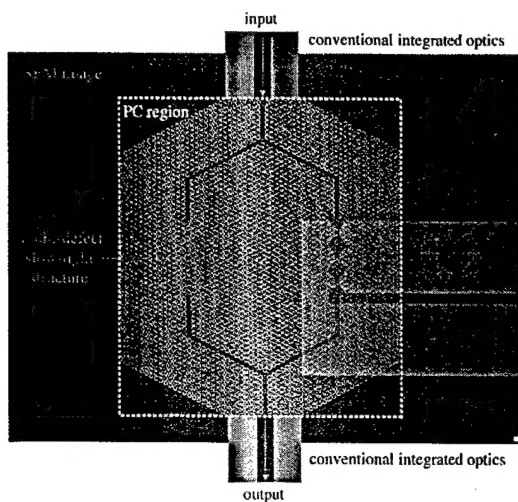
recently shown how these optimizations can be performed in coupled-resonator systems [chen04a, chen04b].



Technical Feasibility

There are two challenges to implementing the vertical mode matching method in 2-D PC slabs: fabrication and materials. We have devised two fabrication methods. The first method utilizes chemical mechanical planarization. In this method, the cladding and core layers are built up sequentially and planarization is performed before the building of the next layer. For example, the slab lower cladding is first etched to define the pillar, then the pillar lower cladding is deposited. The surface is planarized and the slab core layer is deposited. The process repeats until the upper cladding is completed. This process requires two planarization steps and two critical lithography alignments which can be accomplished with modern e-beam systems. The second method first builds up all three pillar layers, then the pillars are defined by lithography/etching. Finally, the three slab layers are deposited. This method has the advantages of no planarization steps and no lithographic alignment; however, it has the disadvantage of requiring a very deep etch. We have also considered materials issues. One very promising class of high index materials is the chalcogenides, which have refractive indices near 2.8 and can be alloyed with silica or nitride for index control. Good optical quality films can be deposited via sputter deposition. Another system is based upon SOI, in which a high index insulator layer is needed for at least one cladding. During a Phase II, we would perform coupled fabrication/modeling to determine the optimal materials and etching/deposition parameters to minimize out of plane losses.

We have test-fabricated one version of the slow-light Mach-Zehnder device as shown in the following figure. Additional components have been added to the SEM image to indicate where electrodes will be placed for the utilization of the thermo-optic effect. This structure has been etched into silicon nitride, which will be used for our initial experiments. Ultimately, during Phase II, we will transfer these designs onto silicon on insulator substrates, first without the use of vertical mode matching, and then with mode matching structures.



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